THE SIGNIFICANCE OF SMALL CRACKS IN FATIGUE DESIGN CONCEPTS AS RELATED TO ROTORCRAFT METALLIC DYNAMIC COMPONENTS

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1. SUMMARY

In this paper the significance of the "small" crack effect as defined in fracture mechanics will be discussed as it relates to life managing rotorcraft dynamic components using the conventional safe-life, the flaw tolerant safe-life, and the damage tolerance design philosophies. These topics will be introduced starting with an explanation of the small-crack theory, then showing how small-crack theory has been used to predict the total fatigue life of fatigue laboratory test coupons with and without flaws, and concluding with how small cracks can affect the crack-growth damage tolerance design philosophy. As stated in this paper the "small" crack effect is defined in fracture mechanics where it has been observed that cracks on the order of 300 microns or less in length will propagate at higher growth rates than long cracks and also will grow at ΔK values below the long crack ΔK threshold. The small-crack effect is illustrated herein as resulting from a lack of crack closure and is explained based on continuum mechanics principles using crack-closure concepts in fracture mechanics.

2. INTRODUCTION

Up to the 1990's rotorcraft fatigue design has combined constant amplitude tests of full-scale parts with flight loads and usage data in a conservative manner to provide "safe life" component replacement times. The replacement times are determined using the Palmgren/Miner nominal stress rule [Ref. 1,2] where the stress versus life curves, S/N curves, are determined from constant amplitude fatigue tests on actual parts that contain no defects or flaws. In contrast to the safe life approach, over the past twenty five years the United States Air Force (USAF) and several other NATO nations have used damage tolerance design philosophies for fixed wing aircraft to improve safety and reliability. The reliability of the safe life approach being used in rotorcraft started to be questioned shortly after presentations at an American Helicopter Society's specialist meeting in 1980 showed predicted fatigue lives for a hypothetical pitch-link problem to vary from a low of 9 hours to a high in excess of 2594 hours. This presented serious cost, weight, and reliability implications. Somewhat later in the 1980's, when the U.S. Army introduced its six nines reliability on fatigue life requirement, attention was starting to shift towards using a possible damage tolerance approach to the life management of rotorcraft dynamic components. In 1983, Sikorsky Aircraft started a damage tolerance assessment of selected HH-53 rotorcraft structure [Ref. 3] through a contract with the USAF. A "type" of damage tolerance requirement for rotorcraft certification [Ref. 4, 5] first appeared in the late 1980's when the Federal Aviation Administration, FAA, added an additional requirement to the federal air regulations (FAR's) requiring a flaw tolerant safe-life evaluation for the larger transport category rotorcraft.

The flaw tolerant safe-life evaluation was introduced in the FAR's to address some of the in-service problems that had begun to appear in rotorcraft that were a result of either manufacturing defects or in-service defects. This new methodology is known by several names. Among them are the "flaw tolerant safe-life" and "enhanced safe-life". Sometimes it is even called damage tolerance, although classic damage tolerance as started by the U.S. Air Force in the early 1970's [Ref.6] assumes that a pre-existing <u>fatigue crack</u> exists in the structure while the flaw tolerant method assumes a <u>flaw</u> (not a sharp fatigue crack) pre-exists in the structure. The flaw tolerant method still uses the Palmgren/Miner rule to establish retirement lives with the applied stress versus life-cycle to crack initiation curves, S/N curves, coming from tests on structures that have pre-existing flaws such as nicks, dents, scratches, and corrosion (to name but a few of these flaw types). The size of these flaws can range from very short measurements of 0.01 mm to as large as the classic USAF damage tolerance crack size of 1.27 mm.

As stated in the flaw tolerant safe-life evaluation as described in the U.S. FAR's [Ref. 4], "the structure, with flaws present, is able to withstand repeated loads

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of variable magnitude without detectable flaw growth..." Since the Palmgren/Miner rule is used to establish the retirement lives in a flaw tolerant analysis, no type of flaw or crack growth analysis is involved. Since about the mid-1980's a trend has been developing to predict total fatigue life (from the first load cycle to failure) using only fatigue crack growth considerations (Newman and his colleagues, Ref. 7). In order for this to be accomplished, a very small initial crack size (1μm to 50μm) is assumed to exist in the structure. It has also been shown recently that total fatigue life can also be predicted on a high strength steel containing a 50 μm machine-like scratch using fracture mechanics concepts and small-crack theory.

In this paper the significance of the "small" crack theory as defined in fracture mechanics will be discussed as it relates to life managing rotorcraft dynamic components using the conventional safe-life, the flaw tolerant safe-life, and the damage tolerance design philosophies. These topics will be introduced starting with an explanation of the small-crack theory, then showing how small-crack theory has been used to predict the total fatigue life of fatigue laboratory test coupons with and without flaws, and concluding with how small cracks can affect the crack-growth damage tolerance design philosophy.

3. SMALL-CRACK THEORY

As stated previously, the crack and flaw sizes that are a part of the flaw tolerant safe-life and the damage tolerance design philosophies range from 0.01 mm to 1.27 mm. To place the size of the cracks considered in small crack theory into perspective with these two design concepts, the sketch as shown in Figure 1 depicts flaws (and cracks) in size from crack formation to failure and shows how they relate to different design philosophies. The size of the cracks in Figure 1 where small-crack theory is shown to apply are very small compared to the USAF damage tolerance crack size (1mm), whereas, for at least one study in a type of flaw tolerant evaluation a tool mark type of flaw was considered with a depth of 0.02 mm [Ref. 8]. Some studies have indicated that the so-called "small" crack effect could exist for cracks as large as 0.30 mm [Ref. 9]. As shown by numerous investigations (Ref. 10-14) these very small cracks have crack growth characteristics that are considerably different than large cracks (cracks longer than 2.0 mm). This "small" crack effect is illustrated in Figure 2 where large crack behavior is shown by the solid curve and small crack behavior by the dashed curves. As seen in Figure 2, these small cracks when described by linear-elastic fracture mechanics (LEFM), grow faster than long cracks at the same stress intensity factor range and grow at stress intensity factors below the long-crack threshold (ΔK_{th}).

The small-crack effect as illustrated in Figure 2 is based on a continuum mechanics explanation of crack growth where the lack of crack-closure, as shown by Newman[Ref. 15], is used to explain the rapid growth and deceleration of small cracks when compared to large-crack behavior. These small-cracks often initiate at inclusion particles, voids, or weak grains where no prior plastic deformation has had time to develop. At the beginning of fatigue crack development, the crack is fully open and thus the stress-intensity factor range is fully effective and the crack-growth rate is faster than in large cracks where crack-closure has developed and thus limited the effective stress-intensity factor range [Ref. 16]. The crack-closure concept as originally conceived by Elber [Ref. 17] concluded that a fatigue crack actually closes under many loading conditions before the minimum cyclic load is reached and that only that portion of the loading cycle where the fatigue crack is said to be "open" contributes to the crack-tip driving force that grows the cracks. Thus, the term the effective stress-intensity factor range has been defined as

$$\Delta K_{eff} = (S_{max} - S_o) (\pi a)^{1/2}\ F \qquad (1)$$

where S_O is the crack-opening stress, a is the crack length, and F is the boundary correction factor which accounts for the effects of structural configuration on the stress intensity factor. Crack-closure has been explained to exist because of residual plastic deformations that remain in the wake of the advancing crack due to yielding adjacent to the crack tip. Small-cracks as shown by the dash curves in Figure 2 are assumed to be fully open since no plastic wake has had a chance to develop, but as the small-crack grows the small crack starts developing a plastic wake and as shown in Figure 2 the dashed curves approach the large-crack results shown by the solid curve. Since the main objective of this paper is to illustrate how small-crack considerations are used in the design concepts previously mentioned (safe-life, etc.), the reader is referred to several references for more detailed explanations of the small-crack theory [Ref. 7 and 13-16].

4. SAFE-LIFE AND SMALL CRACKS

As stated previously the Palmgren/Miner linear cumulative damage rule is normally used in rotorcraft fatigue design to determine safe-life component replacement times. Conservatism's on fatigue strength and flight loads are used to insure that safe-life replacement times are normally calculated [Ref. 18]. In spite of the reasonably good safety record for rotorcraft the safe-life methodology using the Palmgrem/Miner rule has been questioned as being the best method for fatigue design in light of the successful use of the damage tolerance methodology in the fixed-wing community [Ref. 19]. One of the major concerns with the safe-life methodology is the sensitivity of safe-life designed parts to manufacturing and in-service flaws. This stems from the fact that the safe life approach may lead to the selection of wrong materials from a damage tolerance perspective as it gives very little understanding of the physics of the fatigue and fracture process somewhat because of the use of the Palmgrem/Miner rule. Since in the damage tolerance design methodology the growth of fatigue cracks is a primary characteristic in the design procedure, it would be advantageous if a crack growth analysis could be used to help determine replacement times as defined in the safe-life methodology. As stated earlier in this paper, Newman and his colleagues have used a fracture mechanics crack-closure based model along with small-crack growth characteristics to predict total fatigue life of several different metallic materials [Ref. 7,16, and 20].

The main differences in the USAF damage tolerance methodology and the fracture mechanics small-crack total life analysis is the choice of the initial crack size. In the USAF damage tolerance methodology, an inspection interval is often determined for slow growth cracks by integrating a crack growth rate versus stress intensity factor relationship like

$$da/dN = C(\Delta K)^m \qquad (2)$$

where da/dN is the crack growth rate, ΔK is the stress intensity factor range, with C and m being curve fit parameters. In the USAF damage tolerance methodology a safe inspection interval is normally calculated using an initial crack size of 1.27 mm for corner cracks emanating from a hole [Ref. 6]. However, in order to calculate total fatigue life it has been shown that a very small initial crack size (0.001mm to 0.05mm) has to be assumed to exist in the structure in order to use fracture mechanics crack growth concepts to predict fatigue life (safe-life, S/N fatigue behavior).

In the small-crack total life fatigue analysis by Newman [Ref. 16], crack-closure concepts as explained previously, are used to define an effective ΔK and the initial crack length is determined from a small-crack study [Ref. 7,22, and 27]. The expression for ΔK_{eff} from equation (1) is used in equation (2) replacing ΔK with ΔK_{eff} with the crack growth rate as calculated from equation (2) now being expressed as

$$da/dN = C[(S_{max} - S_o) (\pi a)^{1/2} \; F]^m \qquad (3)$$

Total life is then calculated by numerically integrating equation (3) from the initial crack length to failure as

$$N = \sum_{a_i}^{a_f} \frac{\Delta a}{C\left[(S_{\max} - S_o)(\pi a)^{1/2} F\right]^m} \qquad (4)$$

where a_i is the initial crack length as determined from the small crack studies and a_f is the final crack length at failure. Cycles are summed as the crack grows under the applied loading until $K_{max} = K_c$, where K_c is the fracture toughness of the material. When $K_{max} = K_c$, the summation of the load cycles, N, becomes the total fatigue life. A total fatigue life computer algorithm has been developed by Newman [Ref. 26] using the above general procedure which is based on crack-closure concepts in fracture mechanics and small-crack considerations.

This computer program was developed almost two decades ago and was originally conceived as a crack growth analysis tool based on fatigue crack-closure concepts in fracture mechanics and was shown to help explain load interaction effects (crack growth retardation and acceleration) in fatigue crack growth. This computer program was originally called FAST (Fatigue Crack Growth Analysis of Structures), [Ref. 21]. Later the use of "small-crack" concepts were incorporated into FASTRAN [Ref. 26] and this analysis was shown to be very effective in calculating total fatigue life based solely on crack growth data [Ref. 7].

4.1 Small-crack study.

As stated previously, a small crack study of the material is needed to determine the initial crack size to be used in the small-crack total fatigue life analysis. This will be illustrated herein, with the work done by Swain et al. [Ref. 22] where small- and large-crack growth rate data were generated on high strength 4340 steel. The small-crack data were obtained from a single-edge-notch specimen configuration, $K_T = 3.3$ (based on gross stress, not net-section), using the plastic-replica method [Ref. 22]. In this study, small-crack data were measured on 35 fatigue cracks giving information on the distribution of crack-initiation site dimensions. The crack-initiation sites for this 4340 steel were observed to be either a spherical or a stringer particle. The most dominate of these two particles was the spherical (calcium-aluminate) particle which is shown in the scanning electric microscope, SEM, photograph in Figure 3.

To calculate the total fatigue life using the computer algorithm developed by Newman [Ref. 26], an initial crack size is chosen based on the small-crack distributions obtained from small-crack studies. In such a study, a cumulative distribution function of these small-crack defects is often plotted to aid in choosing the initial crack size. Such a distribution is shown in Figure 4 where the cumulative distribution function is plotted against an equivalent semi-circular defect radius based on the actual area of the defect (spherical-inclusion particle). For the high strength 4340 steel used in this study the mean defect was about 13-µm in radius with defects of 8- and 30-µm covering about 80 % of all the defects.

4.2 Fatigue life predictions

Fatigue life predictions using the total life small-crack analysis are shown in Figure 5 compared to constant amplitude test data (symbols) conducted on open-hole test specimens [Ref. 20] at a stress ratio of $R = 0$. The constant amplitude test data at a given stress level exhibits the typical scatter in fatigue lives. Hence, in order to bound the test data, initial crack sizes of 8- and 30-µm were used in the small-crack analysis. The crack configuration chosen for the stress intensity solution was a semi-circular surface crack located at the center of the hole in the specimen's thickness direction. The small-crack analysis is seen to bound the test data very well especially near the endurance limit. However, the analysis tend to predict slightly longer lives at the highest stress level. The reason for this over prediction is not known at this time.

Similar comparisons on high strength 4340 steel have been made with spectrum load fatigue tests [Ref. 20]. Figure 6 shows these comparisons with fatigue test data (symbols) conducted with the standardized helicopter load sequence called Felix/28 [Ref. 23]. The maximum stress in the spectrum is plotted against the cycles to failure. A similar procedure was used for the spectrum fatigue life predictions as was used for the constant amplitude fatigue life predictions. The small-crack analyses with the two initial defect sizes predicted the scatter in the Felix/28 spectrum fatigue tests very well.

5. FLAW TOLERANT SAFE-LIFE AND SMALL CRACKS

In the flaw tolerant safe-life methodology, component retirement times are established using the Palmgrem/Miner rule on structures that have pre-existing flaws such as nicks, dents, scratches, and corrosion. This was done to address some of the in-service problems that appear in rotorcraft that were a result of either manufacturing defects or in-service damage. Since rotorcraft components are often complex configurations as opposed to flat parts, it would not seem unlikely that inadvertent flaws could be put into these components during the fabrication process. This problem was addressed by the rotorcraft industry in the 1980's when the U.S. Rotorcraft Advisory Group (RAG) formed an ad-hoc committee on fatigue methodology to address such issues as abnormally low strength parts which may result from manufacturing process changes or errors, assembly errors, or service-induced damage [Ref. 8]. In the work, presented in reference 8, the affect on the S/N fatigue life of several types of manufacturing defects were evaluated on rotorcraft drive shafting. One of these involved longitudinal tool marks on the drive shaft tube bore which was stated to be "introduced during the extrusion process." A fatigue test was conducted to compare the original fatigue qualification test results to shafts having longitudinal tool marks up to 0.02 mm deep intersecting rivet holes. It was concluded that no significant change in strength resulted from the 0.02 mm deep tool mark. In fact, the fatigue crack origins were not at the tool marks, but at rivet holes not intersected by the tool mark [Ref. 8]. In this study 12 different "degrading" conditions were recommended as defects that should be evaluated in a degraded mode evaluation program. One of these were poor surface finishes and scratches.

The effect on the fatigue life of a machining-like scratch was the focus of a recent study. This study resulted from a structural review of a helicopter which experienced a crash, where one of the fatigue design curves appeared to have one of the data points that defined the design curve as coming from a test article which had a pre-existing flaw in the test article. During the design review this flaw was defined as a surface scratch which occurred during the machining process of the test article. Since the conventional safe-life fatigue design methodology assumes no flaws are present in the structure when a retirement life is calculated, it was felt that this test data point should not have been included in defining the design curve. As a result of this seeming anomaly in the fatigue design curve, a study was initiated to explore the effects of a machine-like scratch on fatigue life.

In the study to assess the affect of machine-like scratches on fatigue life, constant amplitude fatigue tests were conducted at a stress ratio of R = -1 on the same material used in the helicopter where the machine-like scratch test data point appeared on the fatigue life design curve. The material used for this study was 4340 steel heat treated to an ultimate strength of 1448 MPa. The fatigue endurance limit for this heat of material was determined to be about 469 MPa at a stress ratio, R = -1. This agreed with the value given in the Military Handbook 5B [Ref. 24]. Specimens were machined to have a surface finish of 32 rms which is the same finish used on the helicopter parts that were under investigation. The nominal thickness of the test specimens was 8.9 mm. Specimens were machined to an hour glass shape producing an elastic stress concentration factor, K_T, of 1.03 as determined by a boundary force method [Ref. 25]. All fatigue test lives reported in this study were to specimen failure. The machine-like scratch was machined into the specimen surface using an end mill. The scratch was machined across the entire width of the specimen, but only on one side of the specimen. The depth of the scratches was nominally 0.05 mm with the width being about twice the depth. Each specimen scratch was measured to insure uniformity in geometry of the scratches for the test specimens tested in this study. Figure 7 shows the results of the fatigue tests on the specimens with machine-like scratches compared to the pristine specimens. As seen in this figure the endurance limit was reduced from 469 MPa for the pristine specimen to about 276 MPa for the specimen with a 0.05 mm deep scratch. This is a decrease of about 40 percent.

Because of the success shown by the small-crack fracture mechanics model in predicting the total fatigue life of test specimens without flaws, it was logical to try to employ these concepts to predict the fatigue life of the test specimens with the machine-like scratches. As a first step in the analysis of the machine-like scratch, it was decided to use the small-crack analysis to predict the fatigue life of the pristine test specimens (specimens without flaws) in order to check the basic material data input into the crack-growth computer code. The small-crack analysis used was the computer code known as FASTRAN [Ref. 26] which requires several parameters that are a function of the material being analyzed. As stated previously, perhaps the most important parameter is the initial crack size. The long and small crack characteristics of the 4340 steel used in this study were thoroughly investigated as part of an AGARD study done during the 1980's [Ref. 22]. In the study conducted by Swain et al, examination of 35 crack initiation sites described the distribution of initiation sites shown previously in Figure 4 with the dominate initiation site being a spherical (calcium-aluminate) particle as shown in Figure 3. The mean defect size was determined to be a radius of about 13 μm. Using the mean defect size of 13 μm and the surface crack configuration for the stress intensity solution of the defect, the small-crack analysis predicted the pristine test data as shown in Figure 8 quite well. This gave confidence that the basic material data needed for the computer crack-growth code was good. In order to predict the total fatigue life of the machine-like scratch test specimen two approaches were investigated. First, it was thought to model the scratch like a corner or surface crack and use the stress intensity solution for these crack geometries. The applied stress would be assumed to be the K_T of the scratch-like notch times the applied load. However, one of the weaknesses of this approach would be that the fatigue crack would be in the K_T stress field from initiation until failure. The other problem in this approach was to determine the proper K_T to be used. Even though this analysis did a reasonable job in predicting the machine-like scratch test data, the weaknesses of this assumption made this approach unsatisfactory. Finally, the scratch was modeled as a single-edge crack under a tensile loading. In this analysis the crack length was chosen as the average depth of the scratch, 0.051 mm (see Table 1) with the applied stress being the applied load divided by the cross-sectional area of the test specimen. The fatigue life predictions of the machine-like scratch using these input parameters are shown in Figure 8. Here, the agreement between the FASTRAN small-crack analysis and the test data is very good. The results of this study indicate that a fairly robust total fatigue life analysis based only on fatigue crack growth data is emerging as a possible analytical tool for fatigue life assessments using the flaw tolerant safe-life design methodology.

6. SMALL CRACKS AND DAMAGE TOLERANCE

As shown in Figure 1, it would not appear that small-crack theory would need to be considered in the damage tolerance design concept since the small-crack effect appears to affect only cracks of micro-flaw sizes (< 0.1 mm). However, as stated in section 3 on small-crack theory, the small-crack effect has been shown by some studies to be as large as 0.3 mm [Ref. 9]. For rotorcraft design the damage tolerance inspectable flaw size currently being suggested for rotorcraft design is about 0.38 mm. This is only slightly larger than the 0.30 mm small-crack upper limit as determined from the studies reported in reference 9. The research done by Newman and his colleagues have only shown the small-crack effect to exist below 0.1 mm [Ref. 15]. Furthermore, their work has also shown that the small-crack effect is not significant in all materials.

This is illustrated in Figure 9 where small- and large-crack data on 4340 steel is shown at the constant amplitude loading condition of $R = 0$. In this figure the large-crack data is shown by the dashed-dot curve and the small-crack data by the symbols. Also shown in Figure 9 (solid curve) is a prediction of the small-crack growth behavior as determined by the computer code FASTRAN. For most of this data the small- and large-crack data agree very well. In work done by Swain et al [Ref. 22] at a stress ratio $R = -1$, some differences were noted between small- and large-crack data in 4340 steel, but the differences where not overly significant. In research on several materials [Ref. 22, 27] the small-crack effect did not appear to be very dominate at positive stress ratio conditions. The most significant small-crack effects appear to be at negative stress ratios, especially towards $R = -1$.

One area of concern in damage tolerance analysis that small-crack studies have revealed is the magnitude of the large-crack threshold values that are reported in the literature. As shown in Figure 10 where small- and large-crack data on aluminum alloy 2024-T3 data are presented, a large difference exists between the large-crack threshold and the small-crack behavior. Small cracks were shown to grow at ΔK values as low as 0.75 $MPa\sqrt{m}$ which is well below the large-crack ΔK threshold of about 3 $MPa\sqrt{m}$. This large difference between the small-crack growth behavior and the large-crack threshold has caused some researchers to speculate that the large-crack threshold values often reported in the literature are too high (for some materials) and are probably elevated due to the rise in the crack-opening loads as a result of the load-reduction procedure often used to determine the large-crack threshold [Ref. 15].

A series of analyses was recently done to see how a change in the crack-growth threshold, ΔK_{th}, would affect the crack inspection interval which is often a part of a damage tolerance design. The computer code FASTRAN was used for these analyses with the helicopter standardized fatigue load spectrum (Felix/28) being used to represent a typical loading experience. The inspection interval for this analysis was defined as one-half of the crack growth interval from an initial crack size of 0.38 mm (see the first paragraph of this section) to fracture. For this example problem, the material was 4340 steel (ultimate strength of 1448 MPa). A simple laboratory specimen configuration was assumed with a 6.35 mm diameter hole located in the center of a 25.4 mm wide specimen. Specimen thickness was 3.2 mm. To make the problem somewhat realistic the maximum applied stress in the spectrum was chosen to produce an inspection interval of about 500 flight hours (possibly a minimum inspection interval that would not unduly burden the operator). Using an effective ΔK_{th} of 3.2 $MPa\sqrt{m}$, a typical value for 4340 steel at an ultimate strength of 1448 MPa, the maximum stress in the Felix/28 loading spectrum that would give an inspection interval of about 500 flight hours was 150 MPa. Using an increase in the ΔK_{th} of about 40 % (Figure 9 shows small-cracks growing for 4340 steel at about ΔK values of 4.5 $MPa\sqrt{m}$) the inspection interval was only increased by about 15 % (497 hours to 571). Similar analysis were done on the aluminum alloy 7075-T6 and the titanium alloy Ti-6-4 with about the same results as for the 4340 steel. It is standard practice in most design scenarios to have to consider reducing design stresses if certification goals (short inspection intervals, etc.) are not met. Some studies conducted in the rotorcraft community have indicated that reasonable reduction in design stresses can be made in order to obtain practical inspection intervals for use in damage tolerance designs. Some of these studies have also indicated that when the design stresses are reduced the inspection intervals become more sensitive to changes in the crack growth threshold, ΔK_{th}.

7. CONCLUDING REMARKS

In this paper the significance of the "small" crack effect as defined in fracture mechanics was reviewed as it relates to life managing rotorcraft dynamic components using the conventional safe-life, the flaw tolerant safe-life, and the damage tolerance design philosophies. These topics were introduced starting with an explanation of the small-crack theory, then showing how small-crack theory has been used to predict the total fatigue life of fatigue laboratory test coupons with and without flaws, and concluding with how small cracks can affect the crack-growth damage tolerance design philosophy. As stated in this paper the "small" crack effect is defined in fracture mechanics where it has been observed that cracks on the order of 300 microns or less in length will propagate at higher growth rates than long cracks and also will grow at ΔK values below the long crack ΔK threshold. The small-crack effect is illustrated herein as resulting from a lack of crack-closure and is explained based on continuum mechanics principles using crack-closure concepts in fracture mechanics.

A newly emerging analytical tool was illustrated in which a fracture mechanics crack-closure based model which uses small-crack characteristics can predict total fatigue life with reasonable accuracy. This was illustrated on 4340 steel under constant amplitude loading and the standardized helicopter spectra called Felix/28. References were made where this has been also done on aluminum and titanium alloys. This small-crack total fatigue life analysis was shown also to successfully predict the fatigue lives of a laboratory type specimen of 4340 steel with a machine-like scratch with a depth of 0.05 mm. Hence, small-crack fatigue life analysis may be an analytical tool that could used in flaw tolerant safe-life evaluations.

It was stated that it would not appear that small-crack theory would need to be considered in the damage tolerance design concept since the small-crack effect appears to affect only cracks of micro-flaw sizes (1- to -10 µm) where the damage tolerance inspectable flaw size currently being suggested for rotorcraft is about 0.38 mm. However, one area where small-crack considerations could be of benefit would be that of determining the crack-growth threshold, ΔK_{th}. It was illustrated that one aspect of small-crack growth is that they grow at ΔK values below the long crack ΔK threshold. If this situation is real and the "small" crack growth effect is ignored, unconservative predictions of crack growth times to failure might occur since cracks will be growing below the long crack ΔK threshold. Hence, considerations of small-crack growth may help define a more realistic crack-growth threshold.

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Table 1. Scratch Depth Measurements

Specimen No.	Left Edge (mm)	Right Edge (mm)
92	0.0406	0.0406
93	0.0584	0.0559
94	0.0559	0.0533
95	0.0508	0.0559
96	0.0356	0.0381
100	0.0508	0.0406
107	0.0610	0.0737
108	0.0483	0.0533
112	0.0533	0.0635
113	0.0483	0.0660
117	0.0508	0.0457
118	0.0457	0.0406
120	0.0483	0.0559
Average:	0.050	0.052
Total:	0.051	

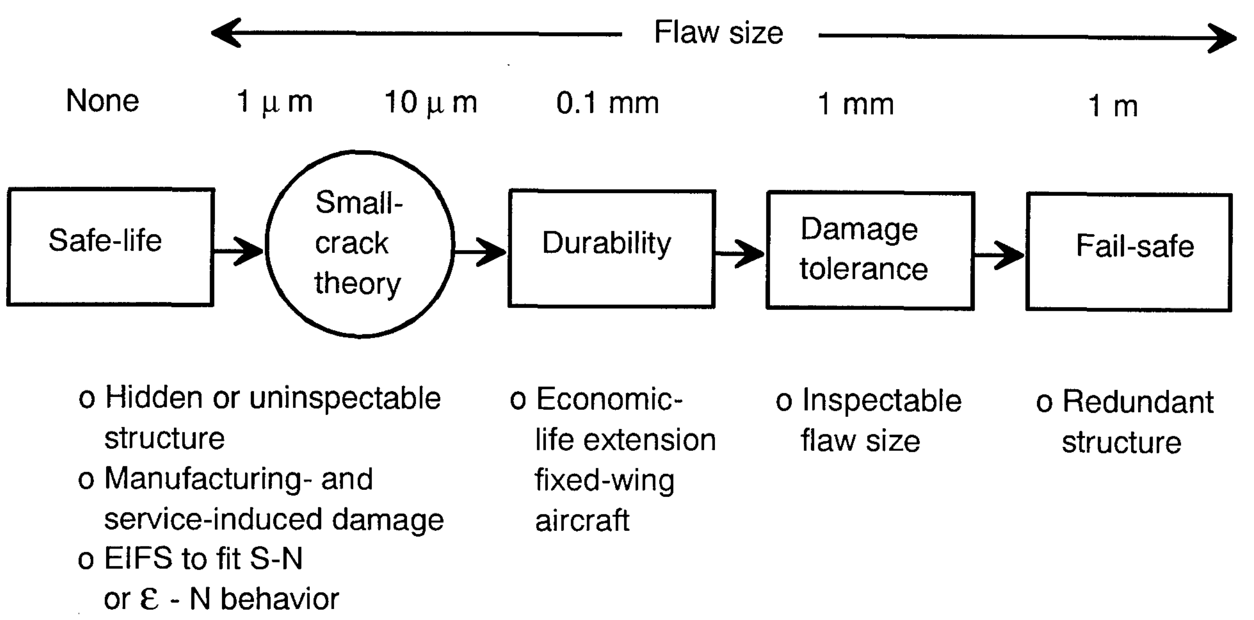

Figure 1. Design concept using small-crack theory (after Ref.15)

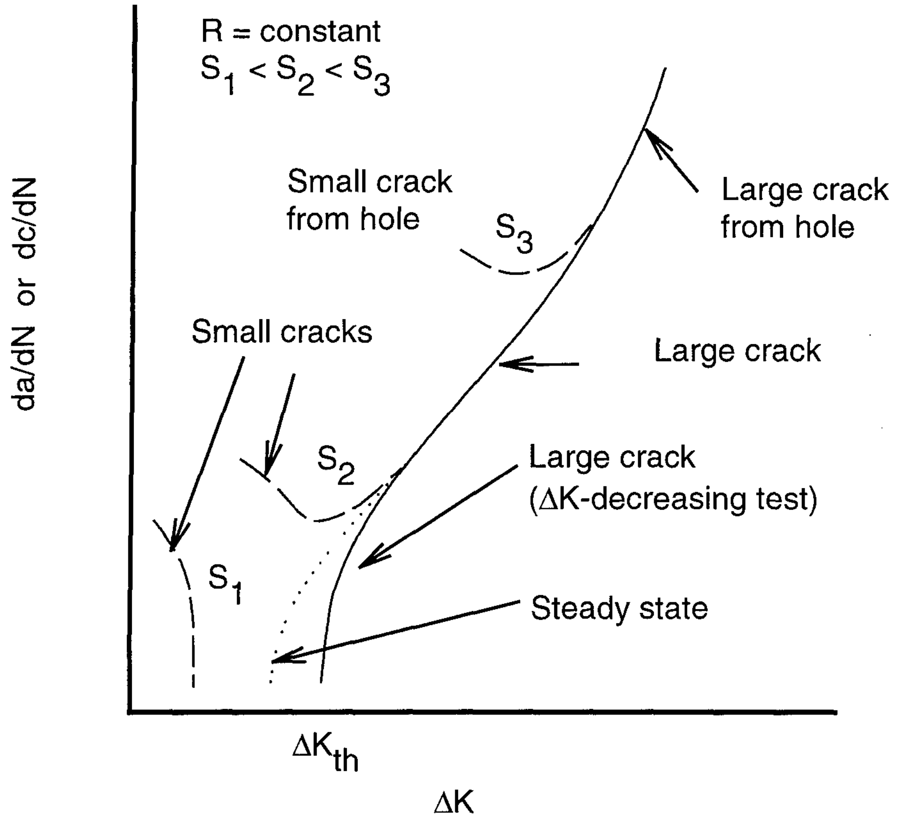

Figure 2. Typical fatigue-crack growth rate data for small and large cracks.

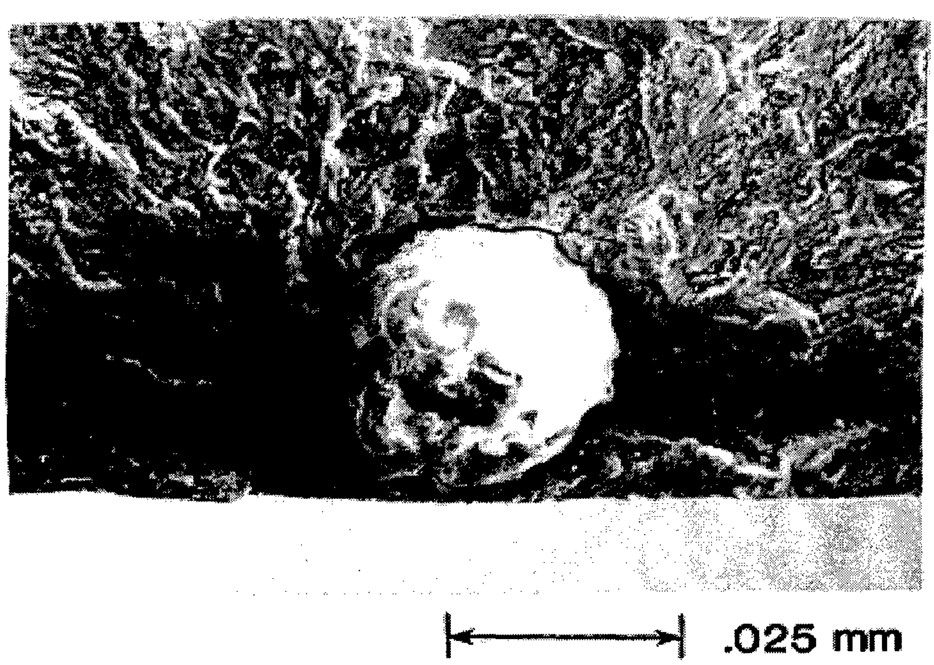

Figure 3. Crack initiation site at spherical-inclusion particle in 4340 steel.

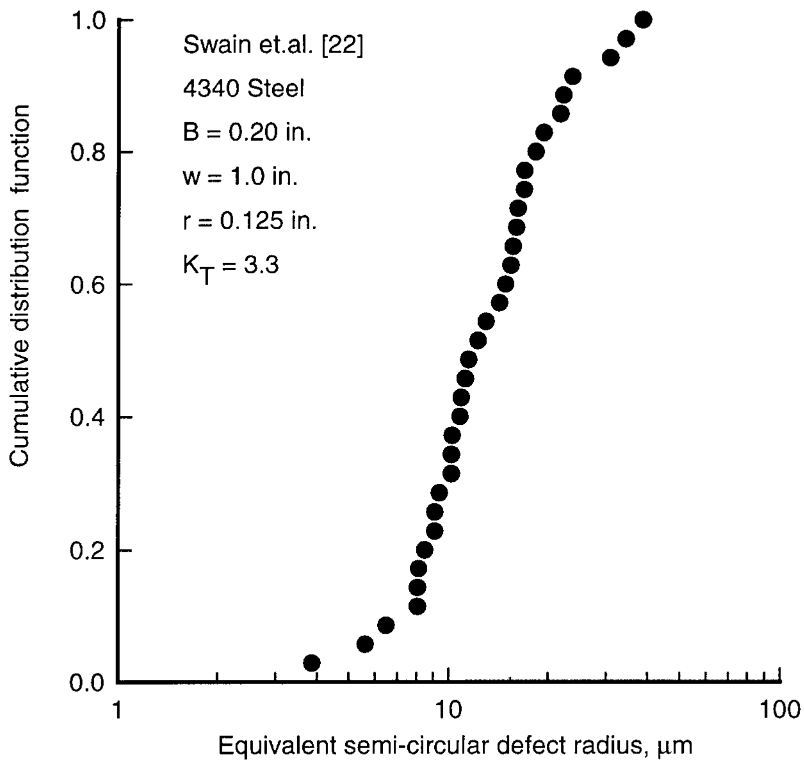

Figure 4. Cumulative distribution function for initiation sites in 4340 steel.

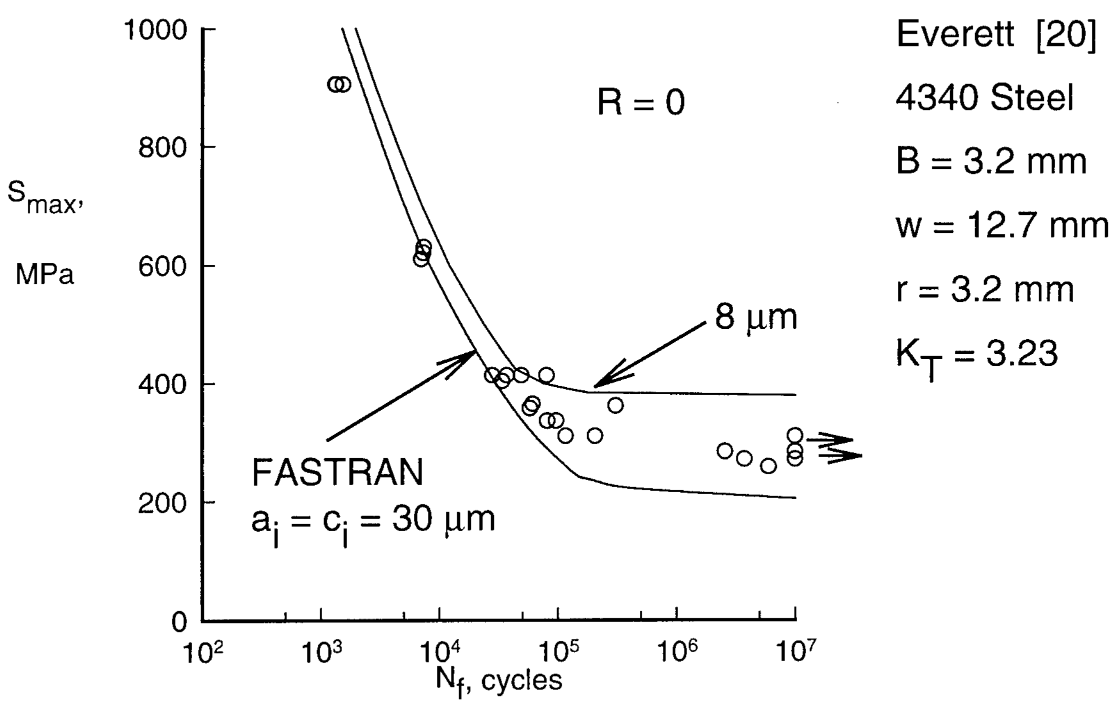

Figure 5. Measure and predicted fatigue live for 4340 steel under constant amplitude loading.

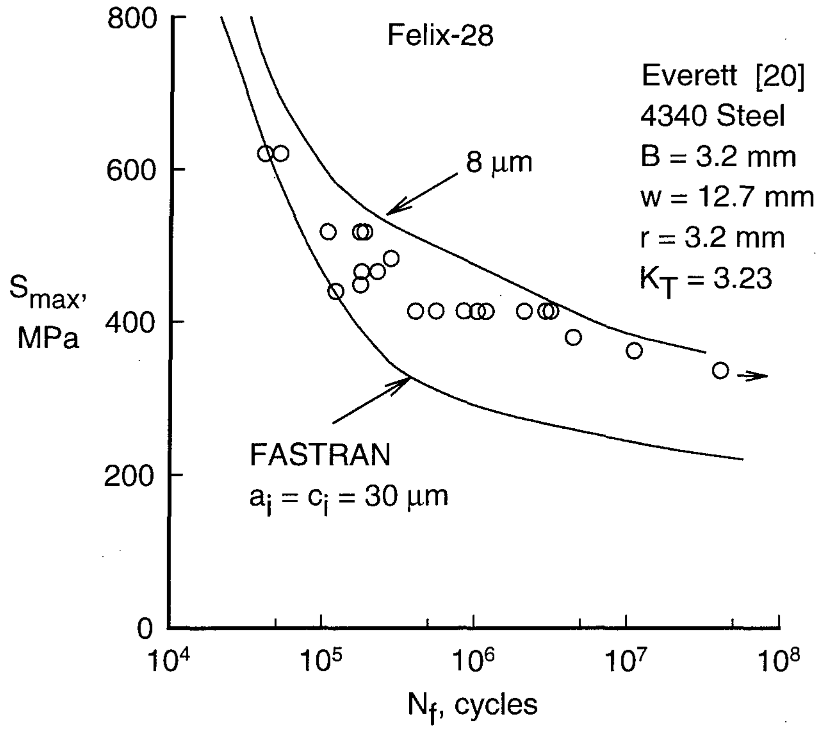

Figure 6. Measured and predicted fatigue lives for 4340 steel under Felix/28 spectrum loading.

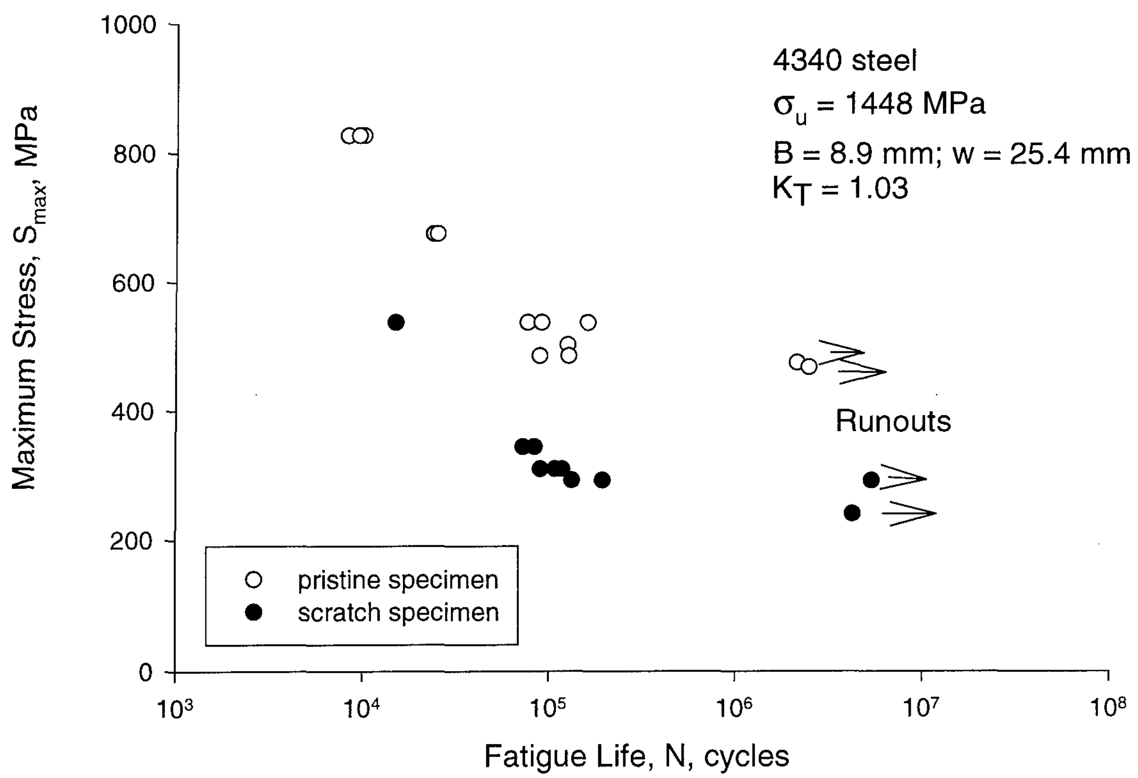

Figure 7. Fatigue life of pristine and scratch specimens under constant amplitude loading at R = -1 with scratch depth of 0.05 mm.

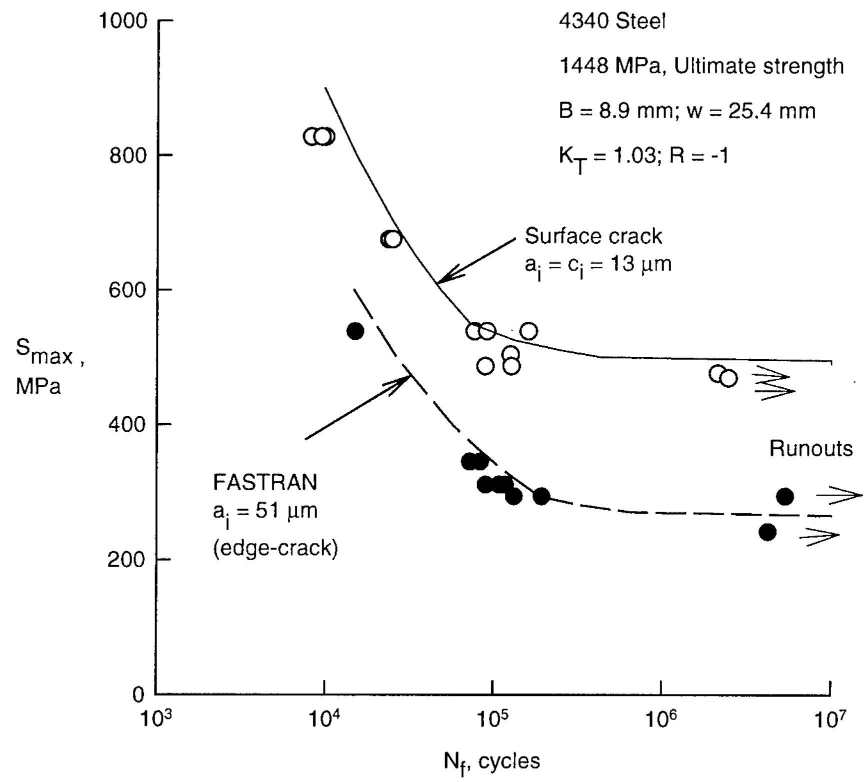

Figure 8. Measured and predicted fatigue lives for the pristine and scratched specimens.

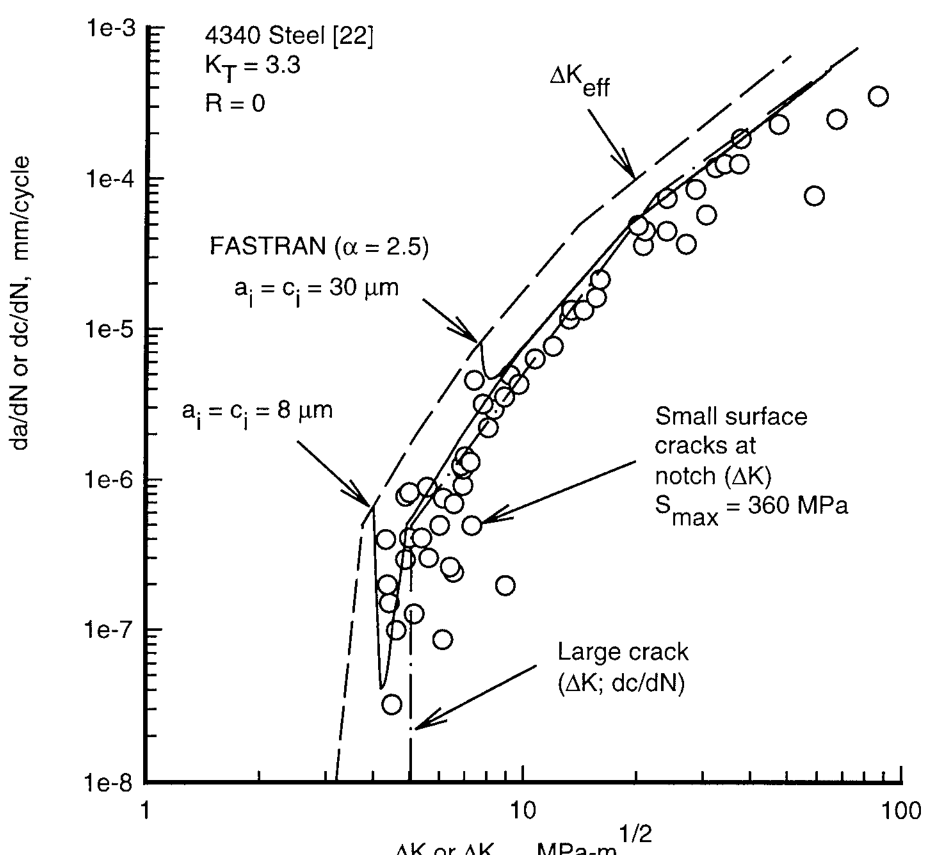

Figure 9. Measured and predicted small corner crack growth at a notch in 4340 steel(after Ref. 28).

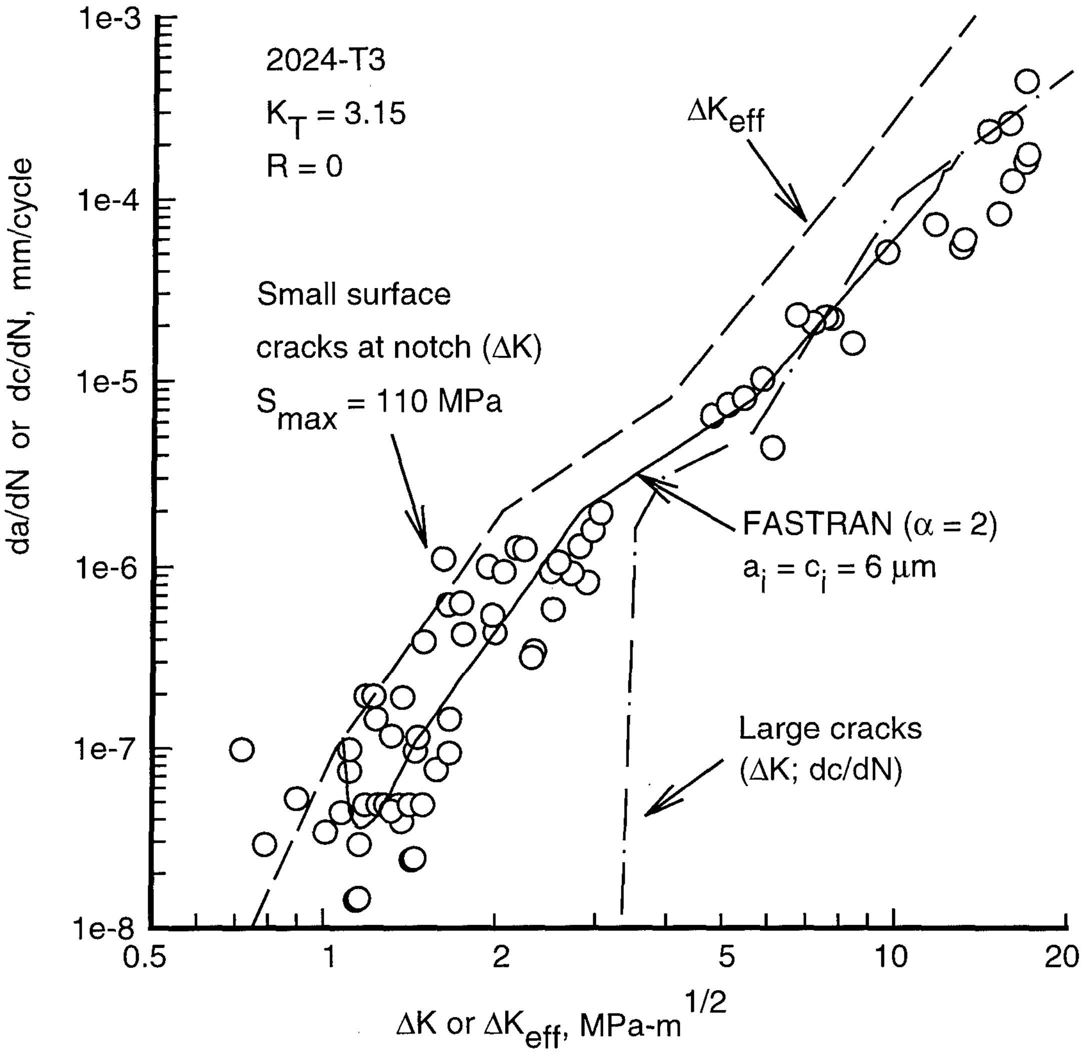

Figure 10. Measured and predicted small surface crack growth at a notch in 2024-T3 (after Ref. 28).